# Towards an effective relativistic density functional for dense matter*

*S. Typel*[1] *and M. D. Voskresenskaya*[1]
[1]GSI, Darmstadt, Germany

Simulations of astrophysical phenomena require the knowledge of the equation of state (EoS) of dense matter in a large range of density, temperature and isospin asymmetry. It is a great challenge to develop theoretical models for dense matter that cover the relevant parameter space in a single approach considering that many important features are governed by different many-body correlations. They can be taken into account in theoretical models by combining various methods in a global effective description.

There is a fundamental distinction between nuclear matter and stellar matter. The former is a theoretical model of strongly interacting particles. It neglects effects of the electromagnetic interaction. At temperatures below approx. 15 MeV, such a system is characterized by a "non-congruent" first-order liquid-gas phase transition in the thermodynamic limit due to the isospin degree of freedom.

The phase diagram of stellar matter displays a very different structure as compared to nuclear matter. Here, the strong interaction and the electromagnetic interaction have to be taken into account with hadrons and leptons as constituent particles. In addition, global charge neutrality is required. The competition of the interactions leads to the formation of finite-size structures such as nuclei and the appearance of a solid, crystalline phase at low temperatures, which occurs in the crust of neutron stars.

By generalizing a relativistic mean-field approach for nuclei and nuclear matter with density-dependent meson-nucleon couplings, a model for dense matter with light nuclei (mass number $A \leq 4$) was developed recently using a density functional formulation [1]. All constituent particles are considered as quasiparticles with medium-dependent properties. In particular, the mass of a cluster, regarded as a many-nucleon correlation, is shifted in the medium. This effect leads to the expected dissolution of nuclei at high-densities. Thus the model successfully exhibits the Mott effect. Different aspects of the formation and dissolution of light nuclei in warm, dilute matter were investigated experimentally and the validity of the theoretical approach was observed [3, 4, 5]. An important aspect is the modification of the symmetry energy of matter at low densities showing an increase as compared to conventional mean-field models without clusterization.

In order to reproduce the virial EoS, which is the correct model benchmark at low densities, it was necessary to incorporate nucleon-nucleon scattering correlations explicitly in the model [2]. They are represented by effective medium-dependent resonance states that appear as new degrees of freedom. A comparison of fugacity expansions leads to consistency relations that connect the strength of the meson-nucleon couplings with experimental scattering phase shifts. The relations require the introduction of effective degeneracy factors for the effective continuum states. Since a part of the many-body correlations is already accounted for in the self-energies of the quasiparticles, the strength of the residual continuum correlations is reduced [6]. The fugacity expansion also indicates relativistic corrections to the standard virial equation of state.

The model is presently extended further by adding heavy nuclei beyond $^4$He using the same theoretical concept as for light nuclei. The shift of cluster masses in the medium is extracted from extensive calculations using the original relativistic density functional with nucleons in an extended Thomas-Fermi approximation in spherical Wigner-Seitz cells with electrons to achieve charge neutrality. Another extension of the model concerns the appearance of mesons (pions, kaons, ...) and heavier hadrons such as hyperons at high densities and temperatures. In the effective density functional the quantum statistics of particles is correctly taken into account with the possibility of boson condensation or nucleon-nucleon pairing. Antiparticles also appear naturally in the relativistic formulation.

The electromagnetic potential appears explicitly only in systems with a spatially inhomogeneous charge density distribution. The effective relativistic density functional approach assumes uniform matter. Hence effects of the Coulomb interaction are considered in an effective description using parametrized results from Monte Carlo simulations of classical one-component plasmas that are generalized to multi-component systems assuming a linear mixing rule. In the solid phase with heavy nuclei placed on lattice sites, the excitation of phonons is described with a Einstein-Debye model adjusted to reproduce known properties of Coulomb crystals. The gas/liquid $\leftrightarrow$ solid phase transition and thermodynamic properties of the crystal can be modeled within such an approach. These effects are presently not included in global EoS tables for astrophysical applications.

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